Recent Progress in the High-Gain FEL Theory

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Introduction

• An exciting path to future x-ray sources: a high-gain FEL operated in SASE mode

• FEL theory well developed in the exponential growth regime (energy spread, emittance, diffraction, guiding)

• Tremendous progress in high-gain experiments
         wavelength down to < 100 nm
         saturation achieved

• Stimulate new developments in high-gain FEL theory, some aspects are discussed in this talk
(mostly based on collaborative work with K.-J. Kim)

Overview

Start-up stage

External signal or spontaneous radiation starts to interact with the e-beam resonantly at undulator λ

Energy modulation ➔ density modulation (microbunching) ➔ coherent radiation at λ ➔

Exponential growth (L_G)

At sufficiently high power, electrons fully microbunched with large energy spread ➔ reach

Saturation (P_{sat})

Log Radiation Intensity

Saturation

Microbunching Begins

Exponential Growth

Start-up

Distance
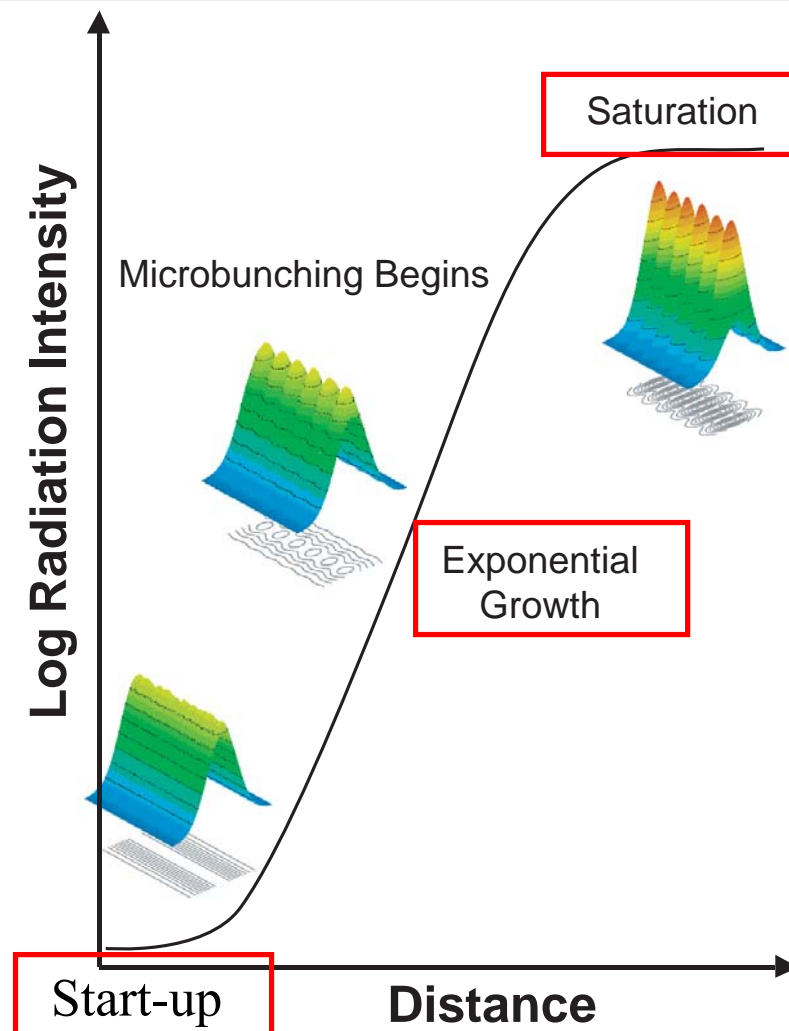
Start-up Process

• Spontaneous emission excites many transverse modes

• FEL instability favors a particular (fundamental) mode

➔ proper modal decomposition for initial value problem

$$\left(\frac{dP}{d\omega}\right)_{\substack{\text{fund.}\\\text{mode}}} = g_A \left[\left(\frac{dP}{d\omega}\right)_{\text{noise}} + \left(\frac{dP}{d\omega}\right)_{\text{signal}} \right] \exp\left(\frac{Z}{L_G}\right)$$

• Effective start-up noise (for SASE): coherent fraction of the spontaneous emission over the first two L_G and can increase with energy spread and emittance through L_G

• 2D Solution determines the radiation energy level in exponential gain regime

Comparison with Time-dependent Codes
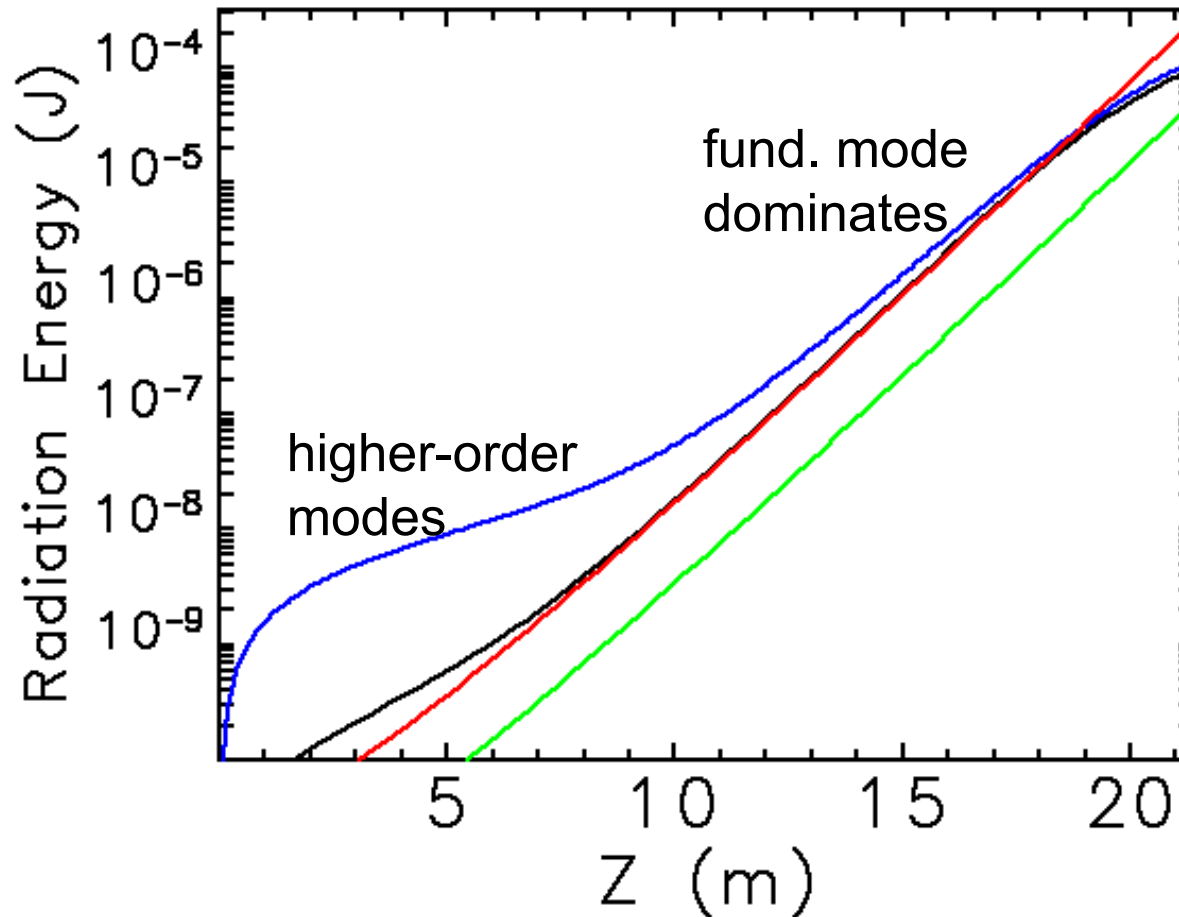
GENESIS 3D

GINGER 2D

Theory 2D

Theory 1D*

* 2D L_G used

Basic Transverse and Temporal Properties

- Diffraction + Gain ➜ transverse mode selection
  - $\Rightarrow$ fundamental mode dominates (gain guiding)
  - $\Rightarrow$ high transverse coherence

- SASE is a chaotic light temporally

$$\text{Coherence length} = \frac{c}{2\sigma_\omega} \approx \frac{\lambda}{4\pi}\sqrt{\frac{N_u}{\rho}} << \text{Bunch length}$$

Intensity fluctuation

$$\frac{\Delta I}{I} = \frac{1}{\sqrt{M}}, \text{ where } M = \frac{\text{bunch length}}{\text{coherence length}}$$

- Statistical fluctuation is large for long-wavelength exps, but much smaller for XFELs (dominated by jitter etc...)

Transverse and Temporal Properties: Interplay

- Transverse coherence somewhat affected by "large" SASE bandwidth (Saldin et al.)
- Different fundamental modes for different frequencies
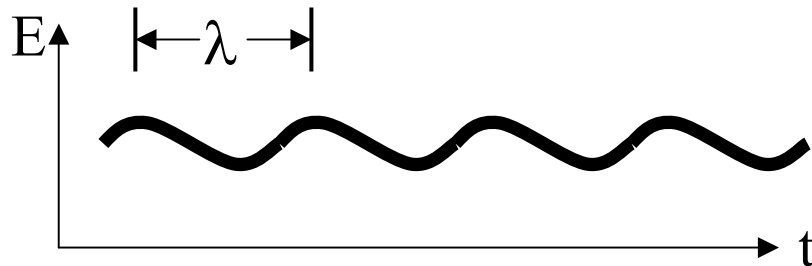
- FEL fundamental mode and its transverse phase space
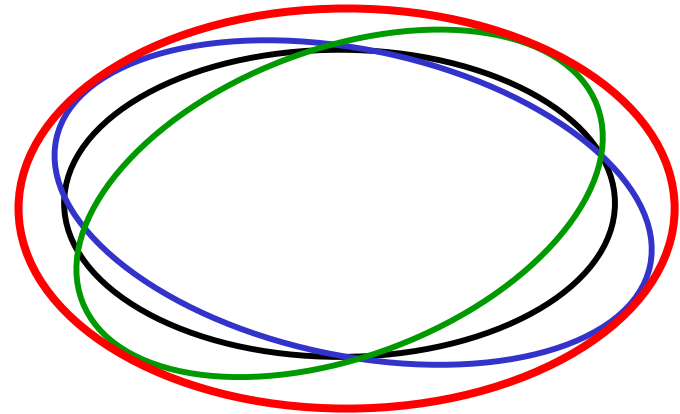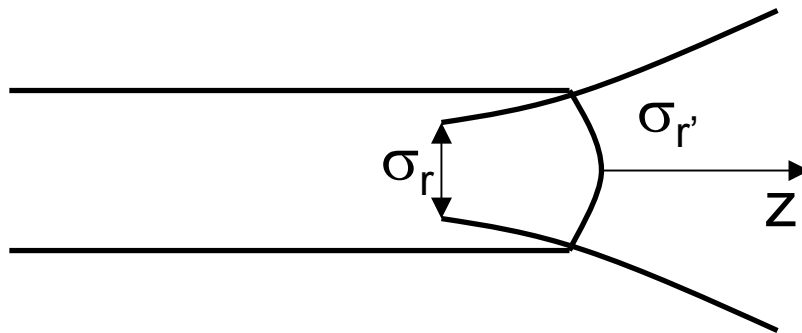
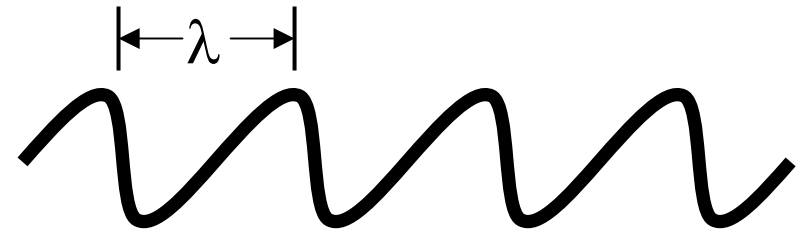- Smearing of radiation phase space ellipses reduces transverse coherence: LEUTL~ 90%, LCLS ~ 97%

Nonlinear Harmonic Generation

- FEL instability creates energy and density modulation at λ,

- Near saturation, strong bunching at fundamental λ produces rich harmonic components

small signal, linear regime   near saturation, nonlinear regime

- Coherent harmonics drive by fundamental λ
  - ➔ gain length = L_G/h (h is harmonic order)
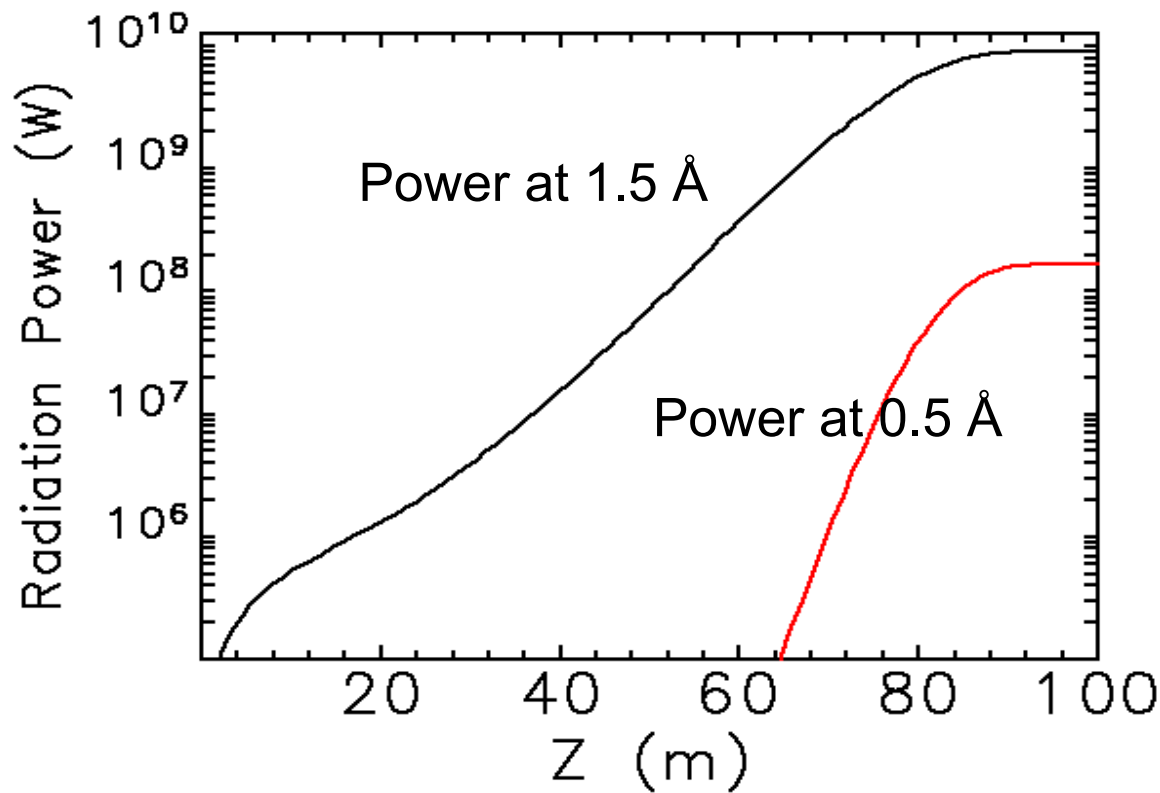 - ➔ transverse coherence
  - ➔ temporal structures
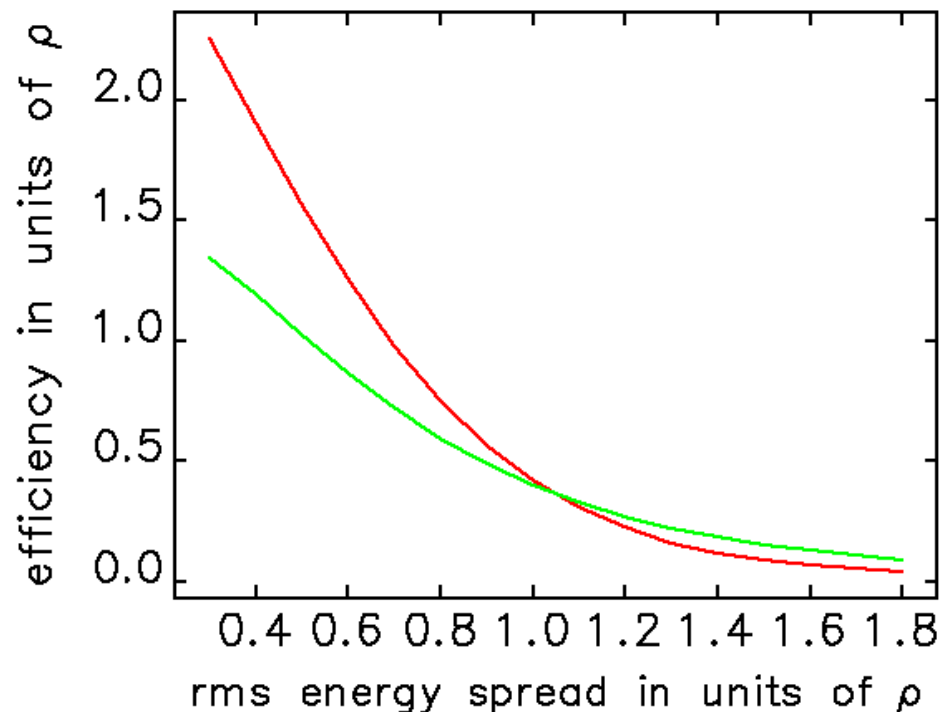
Plenty of Power at (3X) Shorter Wavelength

- Theory predicts third harmonic reaches 1% of fundamental, Verified by recent high-gain experiments

LCLS expectation

Saturation Mechanism

• Quasi-linear relaxation: strong radiation field modifies e-beam distribution ➔ increased energy spread suppress the gain ➔ FEL saturation

- Quasi-linear solution

- Simulation fitting (Xie)

Saturation Behaviors

• XFELs operate in saturation for max. power/stability, seeding schemes go deep saturation to reduce fluctuation

• Electrons trapped by combined radiation+undulator fields

saturation phase space

like an RF bucket

E

H_0

t
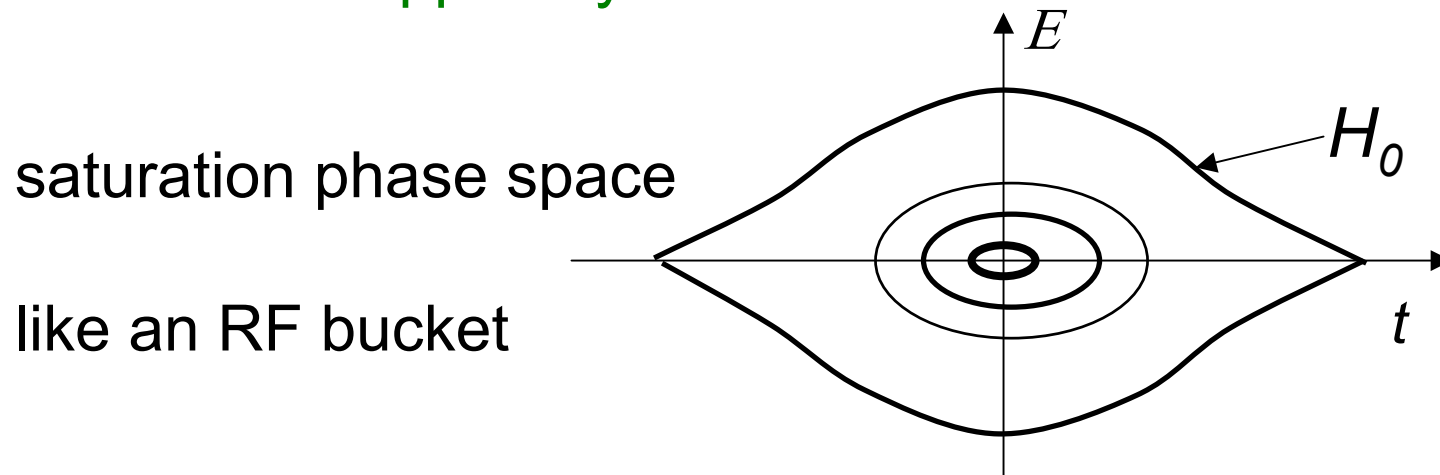
• Radiation power stays roughly constant, but
phase advances due to the beam-radiation interaction
➜ an effective index of refraction (>1) (Scharleman et al.)

Refractive Guiding
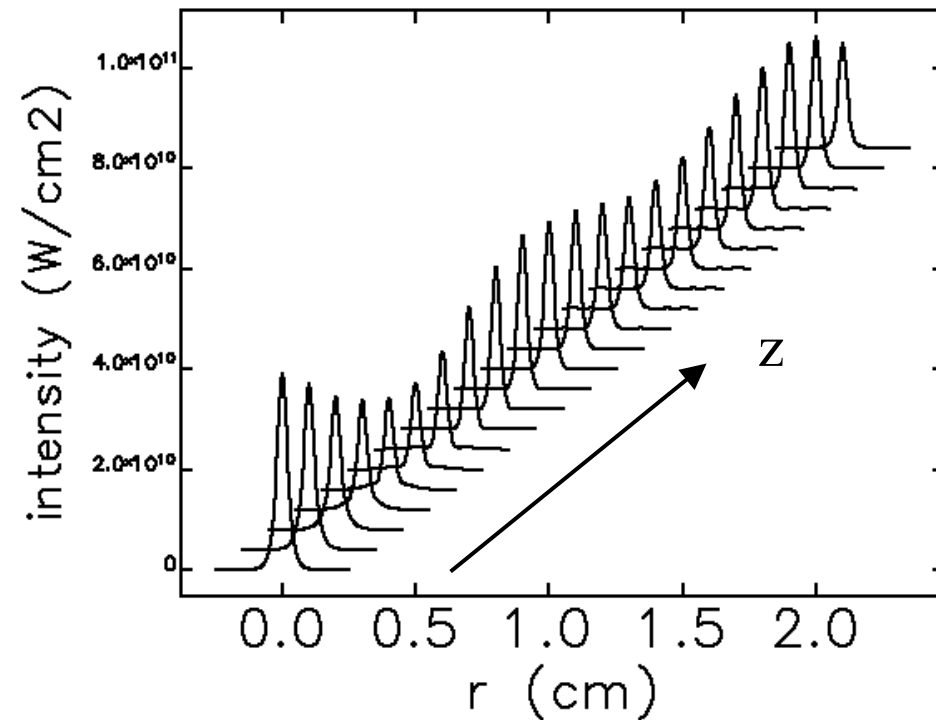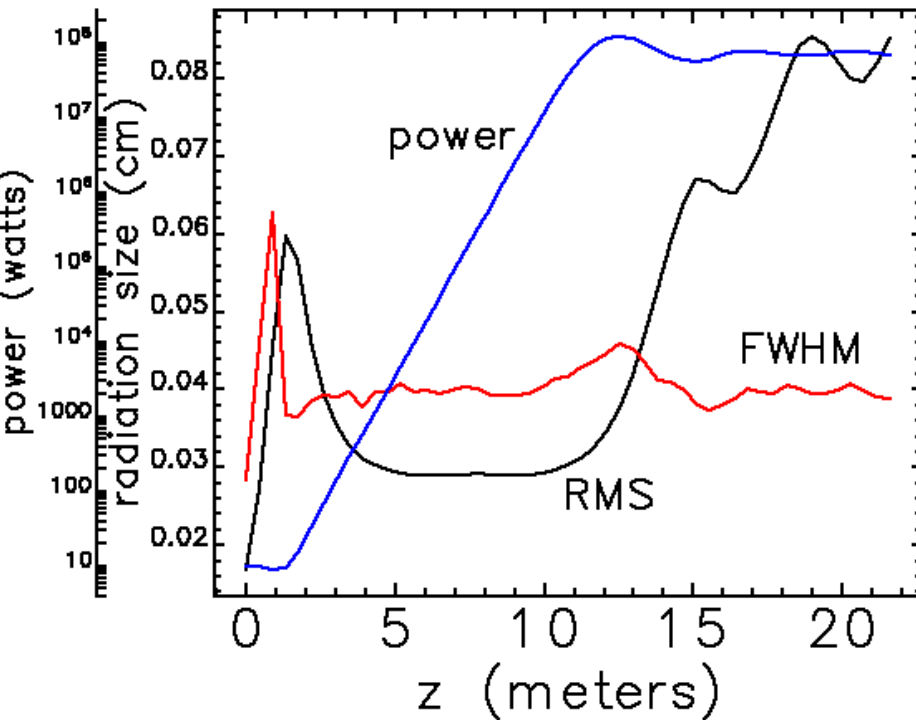
- Guided mode that carries fixed power ➔ constant FWHM
  some excess power diffracts out ➔ increased rms size
 other excess power stays oscillatory

Guided Mode after Saturation
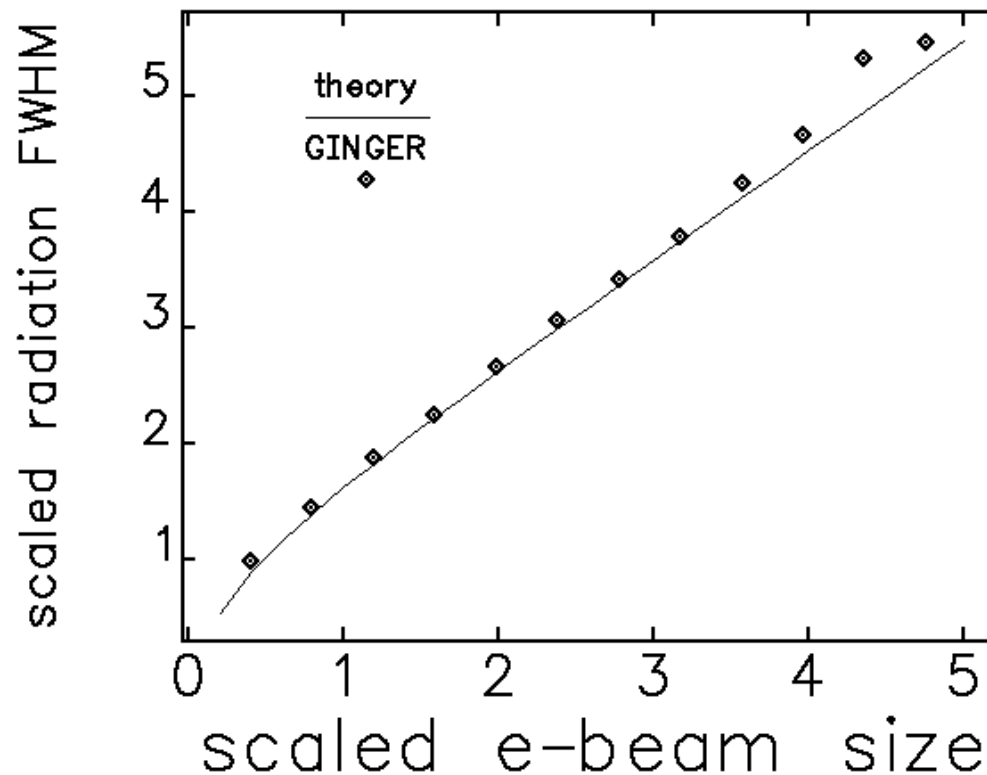
- Valid when emittance < $\lambda/4\pi$
- For XFELs, emittance > $\lambda/4\pi$, any guiding?

Sideband Instability

• Before saturation, SASE spectrum undergoes gain narrowing

• After saturation, spectrum redshifts and broaden because electron's synchrotron motion in the bucket generates sidebands

• LEUTL shows such a behavior (Sajaev et al.)

Average RMS spectrum width
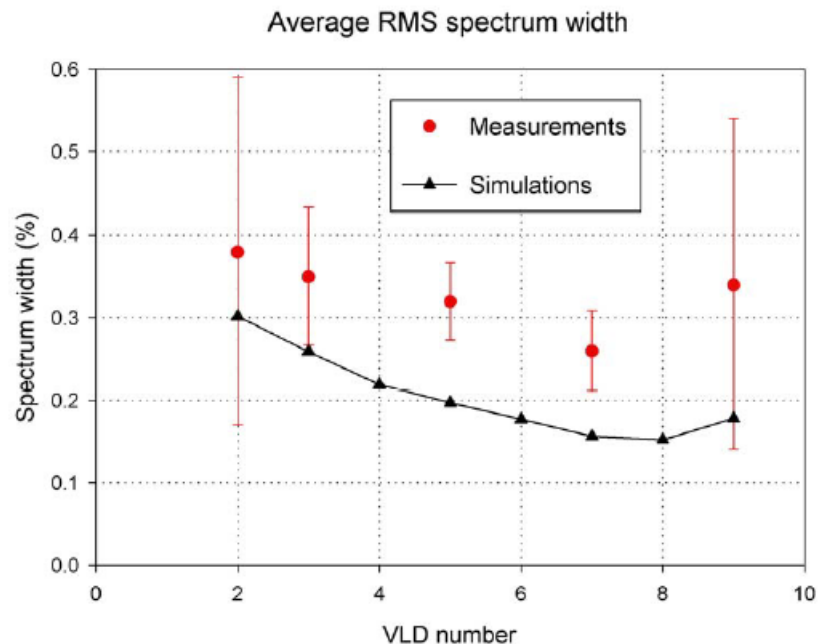
Conclusion

• Evolution of FEL fundamental and harmonic radiation can be completely determined for simple e-beam distributions from start-up to near saturation

• Some understandings of saturation behaviors, more needed in combination with numerical simulations

• Quantum effects (Schroeder et al.) are negligible in XFELs except for quantum fluctuation due to spontaneous radiation (Saldin et al.)

• Excitements of XFELs lead to further progress in all areas of high-gain FEL research (including theory)